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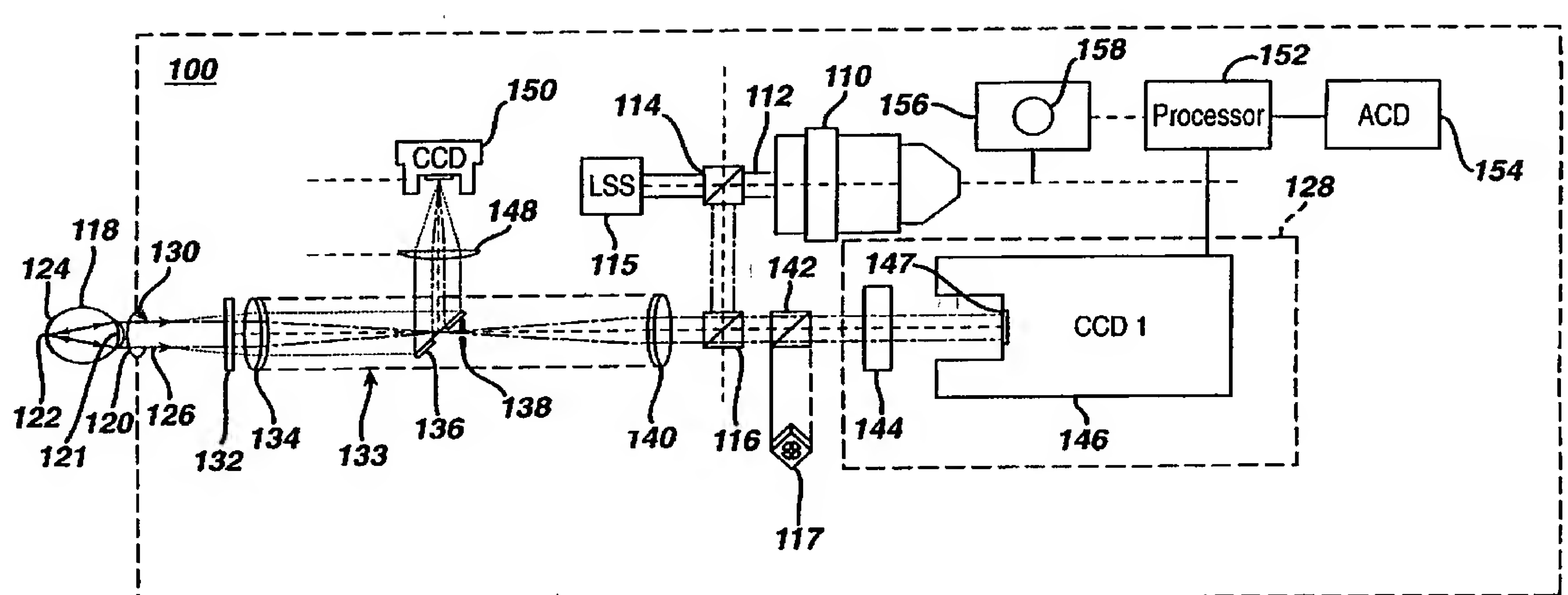
(54) **Title:** WAVEFRONT MEASUREMENT METHOD AND APPARATUS FOR ACCOMMODATING A RANGE OF PUPIL DIAMETERS



(57) **Abstract:** An apparatus and method for measuring wavefront aberrations. The apparatus comprises a magnification device for magnifying the wavefront, a wavefront sensor for capturing information related to the magnified wavefront, and a processor for calculating aberrations of the wavefront from the captured information. The method comprises receiving the wavefront emitted from the pupil at an adjustable lens assembly, adjusting the magnification of the adjustable lens assembly such that the magnified wavefront is optimized for use with the wavefront sensor; and passing the magnified wavefront to the wavefront sensor.

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TITLE: WAVEFRONT MEASUREMENT METHOD AND APPARATUS FOR ACCOMMODATING A RANGE OF PUPIL DIAMETERS

FIELD OF THE INVENTION

The present invention relates generally to optical instruments and, more particularly, to a method and apparatus for measuring wavefront aberrations which can accommodate a range of pupil diameters.

BACKGROUND OF THE INVENTION

The human eye is an optical system which employs a lens to focus light rays representing images onto the retina within the eye. The sharpness of the images produced on the retina is a factor in determining the visual acuity of the eye. Imperfections within the lens and other components and material within the eye, however, may cause the light rays to deviate from a desired path. These deviations, referred to as aberrations, result in blurred images and decreased visual acuity. Hence, a method and apparatus for measuring aberrations is desirable to aid in the correction of such problems.

One method of detecting aberrations introduced by an eye involves determining the aberrations of light rays exiting from within the eye. A beam of light directed into the eye as a point on the retina is reflected or scattered back out of the eye as a wavefront. The wavefront represents the direction of light rays exiting from the eye. By determining the propagation direction of individual portions of the wavefront, the aberrations introduced to the light rays passing through parts of the eye such as the cornea can be determined and corrected. In this type of system, increased accuracy in determining the aberrations can be achieved by reducing the size of the regions of the wavefront used to derive the propagation direction.

A general illustration of the generation of a wavefront is shown in FIG. 1. FIG. 1 is a schematic view of a wavefront 10 generated by reflecting a laser beam 12 off of the retina 20 of an eye 16. The laser beam 12 focuses to a small spot 14 on the retina 20. The retina 20 reflects the laser beam 12, resulting in a point source wavefront 10. The shape and diameter of the wavefront 10 is determined by the shape and size of the pupil 15 within the eye 16, with small pupils producing wavefronts with correspondingly small diameters and large pupils producing wavefronts with large diameters. Ideally, the wavefront 10 from a point source leaving a perfect eye would be represented by a planar wavefront 18. However, aberrations introduced by the eye 16 as the wavefront 10 passes out of the eye 16 result in an imperfect wavefront, as illustrated by the wavefront 24. The wavefront 10 represents aberrations which lead to defocus, astigmatism, spherical aberrations, coma, and other irregularities. Measuring and correcting these aberrations allow the eye 16 to approach its full potential, i.e., the limits of visual resolution.

FIG. 2 is an illustration of a prior art apparatus for measuring the wavefront 10 as illustrated in FIG. 1. By measuring the aberrations, corrective lenses can be produced and/or corrective procedures performed to improve vision. In FIG. 2, a laser 22 generates the laser beam 12 which is routed to the eye 16 by a beam splitter 25. The laser beam 12 forms a spot 14 on the retina 20 of the eye 16. The retina 20 reflects the light from the spot 14 to create a point source wavefront 10 which becomes aberrated as it passes through the lens and other components and material within the eye 16. The wavefront 10 passes through the beam splitter 25 toward a wavefront sensor 26.

A typical prior art wavefront sensor 26 is a Hartman-Shack lenslet array 40 and an imaging plane 28, as illustrated in FIG. 3. The Hartman-Shack lenslet array 40 is an array of lenslets 39. The wavefront sensor 26 samples the wavefront 10 by passing the wavefront 10

through the Hartman-Shack lenslet array 40, resulting in the wavefront 10 producing an array of spots on an imaging plane 28. Generally, the imaging plane 28 is a charge coupled device (CCD) camera. By comparing an array of spots produced by a reference wavefront to the array of spots produced by the wavefront 10, the aberrations introduced by the eye 16 can be computed.

An example of a Hartman-Shack system is described in U.S. Patent Number 6,095,651 to Williams et al., entitled Method and Apparatus for Improving Vision and the Resolution of Retinal Images, issued on August 1, 2000, incorporated fully herein by reference.

Each spot on the imaging plane 28 represents a portion of the wavefront 10, with smaller portions enabling the aberrations to be determined with greater precision. Thus, the smaller the lenslet sub-aperture spacing 42 in the Hartman-Shack lenslet array 40 of FIG. 3, the more accurately the aberrations can be determined. This is especially important for determining aberrations created by small pupils. Since small pupils create a correspondingly small diameter wavefront 10, the wavefront 10 covers fewer lenslets 39 within the lenslet array 40. Therefore, less spots are produced by passing a wavefront emanating from a small pupil through a Hartman-Shack lenslet array 40 than would be produced by passing a wavefront emanating from a large pupil. Hence, a system which is set up to accurately determine the aberrations of a large pupil may not have sufficient sensitivity for measuring the aberrations produced by a small pupil. Conversely, a system which is set up to determined the aberrations of a small pupil may not be able to capture the entire wavefront 10 created by a large pupil, or may produce too many spots, thereby leading to computational complexity in determining the aberrations of the wavefront 10.

The number of spots produced for a small pupil may be increased (thereby increasing the preciseness of the system) by increasing the diameter of the pupil or reducing the size of the lenslets 39 in the Hartman-Shack lenslet array 40. Artificially increasing the diameter of the pupil, however, may introduce aberrations which are not normally present in the eye's normal state, may induce unpredictable results, and will result in aberrations being determined for portions of the eye which are not normally used. Also, reducing the size of the Hartman-Shack lenslet array 40 may require resorting to non-commercially available lenslet arrays, thereby increasing system costs.

In addition to the increased costs associated with lenslet arrays 40 having small sub-aperture 42 spacing, reductions to lenslet sub-aperture spacings 42 are limited due to foldover. Foldover occurs in wavefront sensors 26 having Hartman-Shack lenslet arrays 40 when two or more spots 41A, 41B, 41C, and 41D on the imaging plane 28 overlap. Foldover may result from a lenslet sub-aperture spacing 42 which is too small, or subaperture focal lengths which are too long. Hence, the lenslet sub-aperture spacing 42 must be balanced to achieve good spatial resolution while enabling the measurement of aberrations in wavefronts 10 produced by a wide range of pupil sizes.

Also, traditional Hartman-Shack systems do not contain safety features for ensuring that the laser is operating at a level which is safe for the eye 16, and do not provide for reducing fluctuations in the aberrations of the eye 16.

The constraints imposed by the known Hartman-Shack approaches limit the effectiveness of these systems for accurately determining the aberrations with a high degree of spatial resolution for a wide range of pupil diameters. Accordingly, ophthalmic devices and methods which can accurately measure the aberrations for a wide range of pupil

diameters with a high degree of spatial resolution would be useful. In addition, safety features and methods for reducing fluctuations in the aberrations would also be useful.

SUMMARY OF THE INVENTION

The present invention discloses an apparatus and method for accurately determining the aberrations of wavefronts emanating from eyes having pupils of various diameters. The apparatus includes an adjustable lens assembly for modifying the wavefront emanating from the pupil of the eye. The method includes receiving the wavefront emanating from the pupil at an adjustable lens assembly, adjusting the magnification of said adjustable lens assembly such that the magnified wavefront is optimized for use with a wavefront sensor, and passing the magnified wavefront to the wavefront sensor. The apparatus and method of the present invention are capable of measuring of aberrations with a high degree of spatial resolution for a wide range of pupil diameters.

The wavefront originates as a point source within an eye. The point source is generated by directing a beam of radiation (e.g., a laser) through the eye and reflecting the beam. A beam splitter disposed in the path of the laser beam directs the laser beam to a point on the retina of the eye. The retina of the eye functions as a reflector for reflecting the beam. The wavefront resulting from the reflecting by the retina passes out of the pupil of the eye to the adjustable lens assembly of the present invention. The pupil determines the size and shape of the wavefront as it exits the eye 16. The adjustable lens assembly magnifies the wavefront which is then passed to a wavefront sensor. The wavefront sensor measures distortions of the wavefront as an estimate of aberrations introduced by the eye. Aberrations are then computed by a processor coupled to the wavefront sensor.

In addition to magnification, the present invention discloses a safety circuit for protecting the eye from harmful radiation energy introduced by the laser, and a fixation target for reducing fluctuations of the eye.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic of a wave produced by a laser beam reflected by the retina of an eye;

Figure 2 is a schematic of a prior art apparatus for measuring aberrations introduced by an eye;

Figure 3 is a schematic of a Hartman-Shack lenslet array for use in a prior art apparatus for measuring aberrations;

Figure 4 is a schematic of an apparatus for measuring aberrations introduced by an optical system in accordance with the present invention;

DETAILED DESCRIPTION OF THE INVENTION

Illustrated in FIG. 4 is a preferred embodiment of a wavefront measuring device 100 in accordance with the present invention. In a general overview of the device 100, a radiation source 110 generates a beam 112 which is directed toward an eye 118 through a system of beam splitters, lenses, and apertures. The beam 112 enters the eye 118 through the cornea 120 and pupil 121 where it is focused to a spot 122 on the retina 124 of the eye 118. The spot 122 is reflected by the retina 124 to produce a point source wavefront 126 which travels back out of the eye 118. The wavefront 126 is affected by defects within the eye 118 that cause aberrations, with the diameter of the wavefront 126 projected from the eye 118 determined by the pupil 121. The affected wavefront 126 passes through an adjustable lens assembly 133,

made up of a first lens 134 and a second lens 140, which magnifies the diameter of the wavefront 126. As used herein, the terms magnifies and magnification refer to both enlarging and reducing an image. The wavefront 126 then passes to a wavefront sensor 128 which captures information related to the wavefront 126. The adjustable lens assembly 133 is used to adjust the diameter of the projected wavefront 126 so that it is optimized for use with the wavefront sensor 128, thereby allowing wavefronts 126 emanating from eyes having pupils of different diameters to be measured precisely as further described below.

The radiation source 110 is a device capable of generating a beam 112 of photons, and is preferably a laser diode which produces a polarized beam 112. Additionally, the radiation source 110 may include a spatial filter for correcting noise associated with the radiation source 110. Alternative radiation sources 110 include a laser, light emitting diode (LED), super-luminescent diode (SLD), or essentially any suitable radiation device capable of generating a beam of photons.

In the preferred embodiment, the radiation source 110 is a fiber coupled laser diode. Fiber coupling enables the laser diode to be mounted away from the rest of the assembly to achieve flexibility in positioning and size reduction, and enables a more uniform beam 112 to be produced. If a fiber coupled laser diode is used, an optical module is positioned between the fiber coupled laser diode and the first beam splitter 114 to allow the beam 112 to transition from the optical fiber to the air. In the preferred embodiment, a near infrared source is used to minimize the contracting response of the pupil 121. Minimizing the contracting response maintains the diameter of the wavefront 126 out of the pupil 121 so that the aberrations associated with the eye 118 can be determined accurately.

Semi-conductor lasers such as the laser diode have a lasing threshold current, above which the output power increases exponentially, and the coherence length increases

drastically. In the preferred embodiment, the laser is run in the sub-threshold mode (i.e., below the lasing threshold current). Increased coherence length promotes an effect known as speckle, which results from the laser light interfering optically with itself and leads to measurement problems (i.e., "speckle noise") in the wavefront sensor 128. The measurement problems are due to the speckle effect creating areas of varying intensities across the wavefront 126. If the laser is kept below the threshold, then the power stays low, and the coherence length and the speckle also stay small. In order to operate the laser below its lasing threshold current, a continuously variable laser current supply is used.

The first beam splitter 114 is a device capable of selectively passing and directing beams within the wavefront measuring device 100. Preferably, the first beam splitter 114 is a polarizing beam splitter which selectively passes or reflects the beam 112 based on the polarization of the beam 112. The first beam splitter 114 directs the beam 112 while maintaining the polarization of the beam 112. Non-desirable polarized light within the beam 112 is eliminated by the beam splitter 114 which only reflects portions of the beam 112 having the desired polarization. Since only those portions of the beam 112 having the desired polarization are reflected, non-desirable portions pass through the first beam splitter 114 without being directed toward the main optical axis.

The second beam splitter 116 is also a polarizing beam splitter. It is configured to reflect the polarized beam 112 toward the eye 118 positioned at an output 130 of the device 100 while maintaining the polarization of the beam 112. The second beam splitter 116 is capable of selectively passing and directing beams based on the polarization of the beams.

For the wavefront 126 emanating from the eye 118, the second beam splitter 116 will pass the wavefront 126 toward the wavefront sensor 128. The second beam splitter 116 allows the wavefront 126 to pass because, due to the eye 118 and optics within the system

100, the polarization of the wavefront 126 is 90 degrees out of phase with respect to the beam 112. A non-desirable portion of the polarized light (e.g., light reflected from the various components of the device 100 between the beam splitter 116 and the output 130 of the device 100) within the wavefront 126 are removed by the second beam splitter 116 by reflecting portions of the wavefront 126 having a non-desirable polarization in a direction away from the wavefront sensor 128. The third beam splitter 142 filters out portions of the wavefront 126 having a non-desirable polarization which "leaked" through the second beam splitter 116. The filtered wavefront 126 then passes to the wavefront sensor 128 for determination of the aberrations of the wavefront 126.

The quarter wave plate 132 is an optical component which assists systems 100 of the type illustrated here, i.e. systems which use polarization for routing beams, to distinguish between beams entering the eye 118 and those leaving the eye 118. Prior to reaching the plate 132, the beam 112 is linearly polarized. After passing through the plate 132, the beam 112 is circularly polarized in a right hand direction. The circularly polarized beam 112 is focused to a spot 122 on the retina 124 of the eye 118. The wavefront 126 is produced by reflecting the circularly polarized beam 112 off of the retina 124. The wavefront 126 is circularly polarized in the left hand direction due to the reflection by the retina 124. The diameter of the wavefront 126 is determined by the diameter of the pupil 121 of the eye 118. Alternatively, the plate 132 may circularly polarize the beam 112 in a left hand direction. If the beam 112 is polarized in a left hand direction, the wavefront 126 will be circularly polarized in a right hand direction due to the reflection by the retina 124.

After the wavefront emanates from the eye 118, the quarter wave plate 132 will linearly polarize the circularly polarized wavefront 126 to produce a linearly polarized wavefront 126 having an orientation which is 90 degrees different from the polarization of the

beam 112. With this polarization, the wavefront 126 will be able to pass through the second beam splitter 116 and the third beam splitter 142.

The adjustable lens assembly 133 is made up of first lens 134 and second lens 140 which act as a telescope. The focal lengths of the first lens 134 and the second lens 140 are chosen such that the wavefront 126 will be optimized for use with the wavefront sensor 128. The ratio of the focal lengths of the first lens 134 and the second lens 140 determine the angular magnification of the lens assembly 133. By moving the lenses in relation to one another, the wavefront 126 emanating from the pupil 121 of the eye 118 can be magnified to optimize the wavefront 126 for use with the wavefront sensor 128. Alternatively, a multi-element zoom lens system may be used to perform the angular magnification.

An adjustment control 156 is used to move the lenses in relation to one another. The adjustment control 156 may be manually adjusted through the use of a control knob 158 or computer controlled by the processor 152. In the preferred embodiment, the movement is manually controlled by shifting all of the optical components within the device 100 except for the wave plate 132 and the first lens 134. Alternatively, the wave plate 132 and the first lens 134 may be adjusted in relation to the rest of the device 100. Various arrangements for changing the relationship between the first lens 134 and the second lens 140 will be readily apparent to those skilled in the art and may be used without departing from the scope and spirit of the present invention.

The pinhole 138 is an aperture positioned between the first lens 134 and the second lens 140, and is used to block reflections from specular surfaces, e.g., the cornea and crystalline lens of the eye 118. Both surfaces of the cornea and crystalline lens of the eye 118 are potential sources for this kind of signal. In a preferred embodiment, the first lens 134 will

focus the wavefront 126 through the pinhole 136 and the second lens 140 will collimate the wavefront 126.

In the preferred embodiment, the wavefront sensor 128 is a known wavefront sensor made up of a Hartman-Shack lenslet array 144 and an imaging device 146. An array of spots is produced by passing the wavefront 126 through the Hartman-Shack lenslet array 144 as described previously. The array of spots are passed to the imaging device 146 for measurement.

The imaging device 146 is capable of precisely detecting the location of energy incident to an imaging plane 147. Preferably, the imaging device 146 is a charge coupled device (CCD) camera. A charge coupled camera is a device capable of converting energy incident to the imaging plane 147 into a digital representation. Charge coupled devices are well known and a suitable device for use with the present invention would be readily apparent to those skilled in the art.

In a preferred embodiment, the magnification ratio of the lens assembly 133 is between approximately 3:1 and 1:3, and the wavefront sensor 128 is a Hartman-Shack wavefront sensor 128 having a lenslet array 144 with approximately a 300 micron pitch, e.g., a standard Hartman-Shack lenslet array. Preferably, the size of the subapertures within the lenslet array 144 are chosen such that a subject with a 3mm pupil would produce at least a 10x10 array of spots.

It will be readily apparent to those skilled in the art that wide variations in the magnification ratio of the lens assembly 133 and the pitch of the lenslet array 144 would be within the scope of the present invention. In addition, it will be understood that different types of wavefront sensors 128, such as wavefront sensors incorporating aberroscopes and digital micro-mirror devices (DMD™) are within the scope of the present invention.

The processor 152 receives information from the imaging device 146 and computes the aberrations by using software to analyze the information. Either a square, or a circular (octagonal) region can be analyzed. Preferably, the information is analyzed using known techniques, e.g., Zernike polynomials which are defined on a unit circle. In the preferred embodiment, a circular region is used because it uses more of the data and provides a closer implementation of the Zernike polynomials for analysis. The analysis can be implemented using known programming techniques. The information may be stored in a storage register prior to processing by processor 136 or may be processed immediately. It is apparent to those skilled in the art that the receipt of information from the imaging device 146 and the processing of information may be performed by a single processor 152 or divided among a plurality of processors.

In accordance with certain embodiments of the present invention, the aberration correction device 154 is coupled to the processor 152. Alternatively, information calculated by the processor 152 may be stored on a hard drive, diskette, server, compact disc, digital versatile disc, or essentially any device capable of storing information. The stored information is then passed to an aberration correction device 154. The aberration correction device 154 includes a known lens grinder, contact lens manufacturing system, surgical laser system, or other optical system correction device. In a surgical laser system, a laser can be optically positioned relative to a beam splitter for directing a laser cutting beam toward the cornea 120 of the eye 118, in a manner well known in the art, for the purpose of performing ophthalmic surgery.

In accordance with other certain embodiments of the present invention, a laser safety circuit 115 is employed to ensure that the power of the beam 112 is safe for the eye 118. The laser safety circuit 115 contains a photodetector, and a circuit coupled to the photodetector

which compares the portions of the beam 112 coming through the beam splitter 114, due to "leakage" and portions of the beam 112 having a polarization different than the polarization of the beam splitter 114, to a calibrated electronic reference signal corresponding to a pre-determined safe laser exposure (e.g., about 200uW.) The circuit is connected to a relay which will open and cut power from the laser 110 if a signal generated by the circuit exceeds the level of the reference signal or if power is removed from the system. Resetting the relay is manual, and is performed with the laser on and running at a power level which is less than the reference level. In this manner, it is fail-safe. It will be readily apparent to those skilled in the art that the laser safety circuit 115 could be integrated into the system 100 at different locations and in a different manner without departing from the spirit of the present invention.

In accordance with embodiments utilizing a laser safety circuit 115, the electronic reference signal is determined by detecting an acceptable power output (e.g. 200uW) at an output 130 (i.e., a spot where the beam 112 leaves the wavefront measuring device 100) just before the eye 118 and determining the amount of power detected by the photo-detector during a calibration procedure. The photo-detector detects the portion of the beam 112 which passes through the first beam splitter 114. The amount of power detected by the photo-detector at the time of calibration corresponds to an acceptable power output of the laser 110. The circuit of the laser safety circuit 115 uses the power detected by the photo-detector to generate the electronic reference signal. Generally, the laser is run below 80uW, however, the laser safety circuit 116 provides additional protection.

In accordance with other certain embodiments, a fixation target 117 is incorporated for the eye 118 to focus on, thereby reducing fluctuations in the aberrations of the eye 118. In a preferred embodiment, the beam splitter 142 is used to incorporate the fixation target 117

into the system 100. This configuration allows light from the fixation target 117 to be placed along the same path as light from the radiation source 110 that is heading toward the eye 118. The fixation target 117 is an optional component which provides a focusing point for the person whose eye 118 is being scanned, thereby controlling eye movements and accommodation (focusing).

In accordance with yet other certain embodiments, an optional mirror 136 is located near the focal point of the first lens 134. As the wavefront 126 passes through the first lens 134 it is focused to the focal point of the first lens 134. The optional mirror 136 contains a small hole which allows the wavefront 126 to pass through the mirror. Ambient light reflected by the eye 118 strikes the first lens 134 at a greater angle than the wavefront 126, and therefore is not focused to the focal point of the first lens 134. The optional mirror 136 directs the light which is not focused to first lens' 134 focal point toward a camera 150. This camera 150 is used to adjust the position of the eye 118 such that an image of the iris of the eye 118 is centered on the monitor. If the iris of the eye 118 is centered on the monitor, the image out of the eye 118 will be centered on the Hartman-Shack lenslet array 144, and the spot pattern produced by the lenslet array 144 will be centered on the imaging device 146.

Having thus described a few particular embodiments of the invention, various alterations, modifications, and improvements will readily occur to those skilled in the art. For example, the number of beam splitters used in the system of the present invention will very depending on the layout of system components and the features included in the system. In addition, if a non-polarized beam source and beam splitters are used, a plate for converting between linear polarization and circular polarization will not be required. Such alterations, modifications and improvements as are made obvious by this disclosure are intended to be

part of this description though not expressly stated herein, and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description is by way of example only, and not limiting. The invention is limited only as defined in the following claims and equivalents thereto.

What is claimed is:

1. An adjustable lens apparatus for optimizing the projection of a wavefront emanating from a pupil of an eye onto a wavefront measuring device, said apparatus comprising:

an adjustable lens assembly having a first side adapted to receive the wavefront emanating from the eye and a second side for emitting a magnified image of the wavefront toward an imaging device, said adjustable lens assembly positioned between the pupil of the eye and the wavefront measuring device; and

a control coupled to said adjustable lens assembly for adjusting the magnification of said adjustable lens assembly.

2. An apparatus in accordance with claim 1 further comprising:

a processor coupled to said control for adjusting the magnification of said adjustable lens assembly.

3. An apparatus in accordance with claim 1 further comprising:

a manual adjustment device coupled to said control for adjusting the magnification of said adjustable lens assembly.

4. An apparatus in accordance with claim 1, wherein said adjustable lens comprises:

a first lens positioned at said first side; and

a second lens positioned at said second side along the same optical axis as said first lens, and

wherein the magnification of said adjustable lens assembly is determined by the position of said first lens and said second lens relative to one another.

5. An apparatus in accordance with claim 4, wherein said adjustable lens has a magnification ratio between about 3:1 and about 1:3.

6. An apparatus for measuring aberrations of a wavefront emitted from a pupil of an eye, comprising:

a radiation source for generating a beam to be directed to the eye;

an adjustable lens assembly having a first side adapted to receive the wavefront emitted from the eye and a second side for emitting a magnified image of the wavefront;

a control coupled to said adjustable lens assembly for adjusting the magnification of said adjustable lens assembly; and

a wavefront measuring device for receiving said magnified image of the wavefront and determining the aberrations of the wavefront.

7. An apparatus in accordance with claim 6, wherein the wavefront measuring device comprises a Hartman-Shack lenslet array.

8. An apparatus in accordance with claim 7, wherein the Hartman-Shack lens array has about a 300 micron pitch.

9. An apparatus in accordance with claim 8, wherein said adjustable lens has a magnification ratio between about 3:1 and about 1:3.

10. An apparatus in accordance with claim 6, wherein said adjustable lens comprises:

a first lens positioned at said first side; and

a second lens positioned at said second side along the same optical axis as said first lens, and

wherein the magnification of said adjustable lens assembly is determined by the position of said first lens and said second lens relative to one another.

11. An apparatus in accordance with claim 6, further comprising:

a safety circuit having an input for monitoring said beam and an output coupled to said radiation source for deactivating said radiation source if said beam exceeds a predefined intensity.

12. An apparatus in accordance with claim 6, further comprising:

a fixation target; and

a beam splitter for directing an image of said fixation target toward said eye.

13. An apparatus in accordance with claim 6, wherein said radiation source in a fiber coupled laser diode.

14. An apparatus in accordance with claim 6, wherein said wavefront measuring device determines the aberrations of the wavefront using circular analysis regions.

15. An apparatus in accordance with claim 6, further comprising a quarter wave plate positioned between the beam and the eye.

16. A method for optimizing a wavefront emitted from a pupil of an eye for detection by a wavefront measuring device comprising the steps of:

(a) receiving the wavefront emitted from the pupil at an adjustable lens assembly;

(b) adjusting the magnification of said adjustable lens assembly such that the magnified wavefront is optimized for use with the wavefront measuring device; and

(c) passing the magnified wavefront to the wavefront measuring device.

17. An apparatus for reducing fluctuations of an eye in an ophthalmic wavefront measuring device having a laser for generating a beam to be directed into the eye for generating a wavefront out of the eye and a wavefront measuring device for measuring aberrations within the wavefront, said apparatus comprising:

a fixation target; and

a beam splitter for directing an image of said fixation target toward the eye;

wherein said fixation target is visible to the eye for reducing fluctuations in the eye during the measurement of the aberrations of the wavefront.

18. A safety apparatus for use in an ophthalmic wavefront measuring device having a laser for generating a beam to be directed into an eye for generating a wavefront out of the eye and a wavefront measuring device for measuring aberrations within the wavefront, said apparatus comprising:

a photodetector positioned to receive a portion of the beam;

a safety circuit having an input configured to receive a signal from said photodetector corresponding to the intensity of the beam, a compare circuit for comparing the signal from said photodetector to a calibrated reference signal, and an output coupled to the laser for deactivating the laser if the signal from said photodetector indicates that the beam exceeds a predefined intensity.

FIG. 1

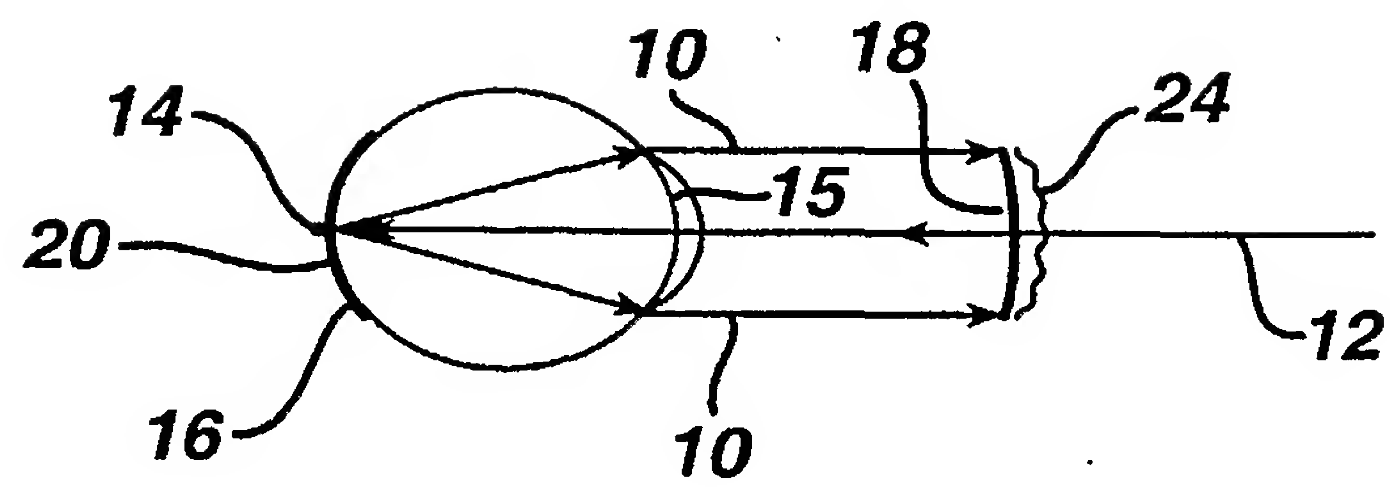

FIG. 2 PRIOR ART

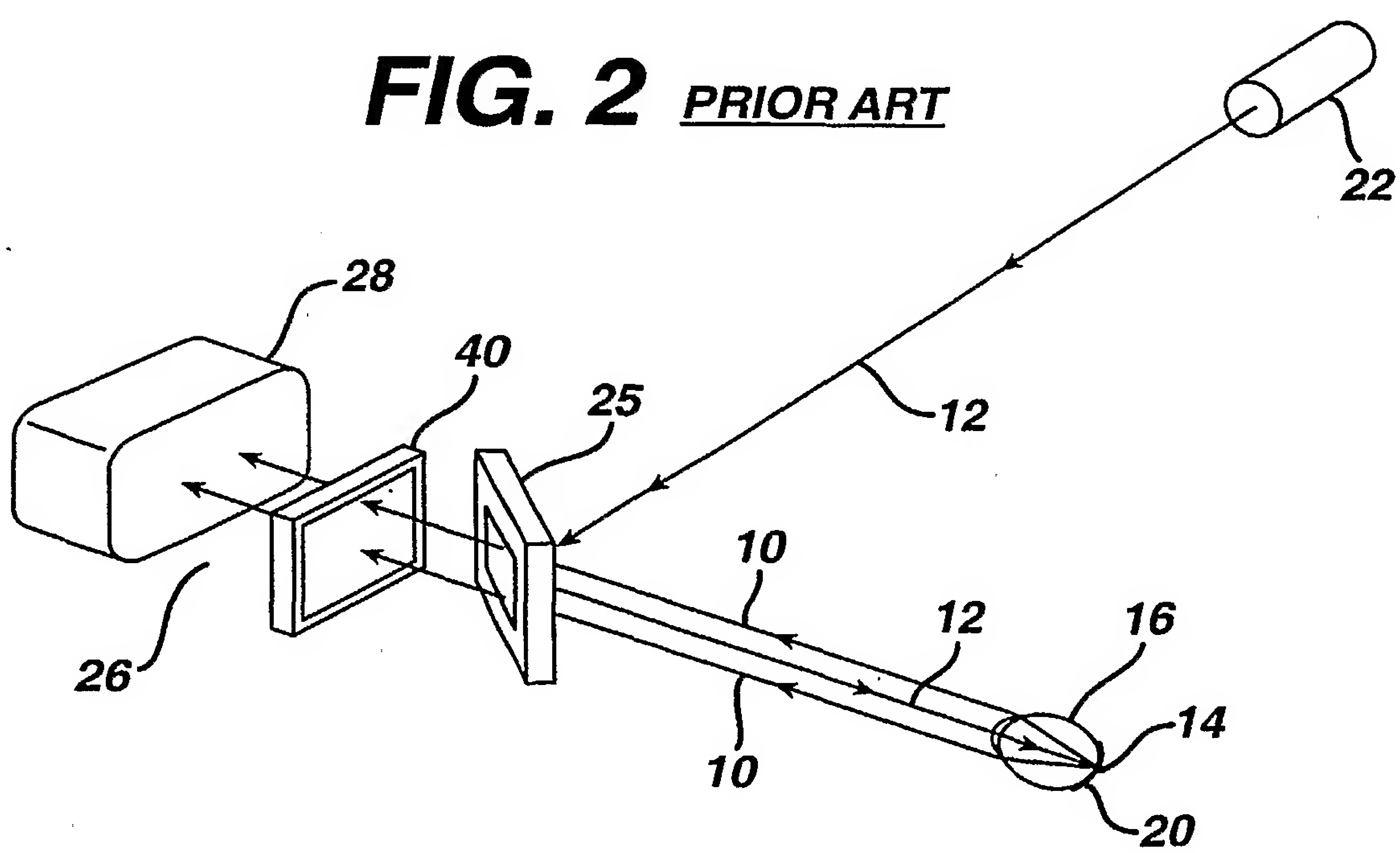

FIG. 3 PRIOR ART

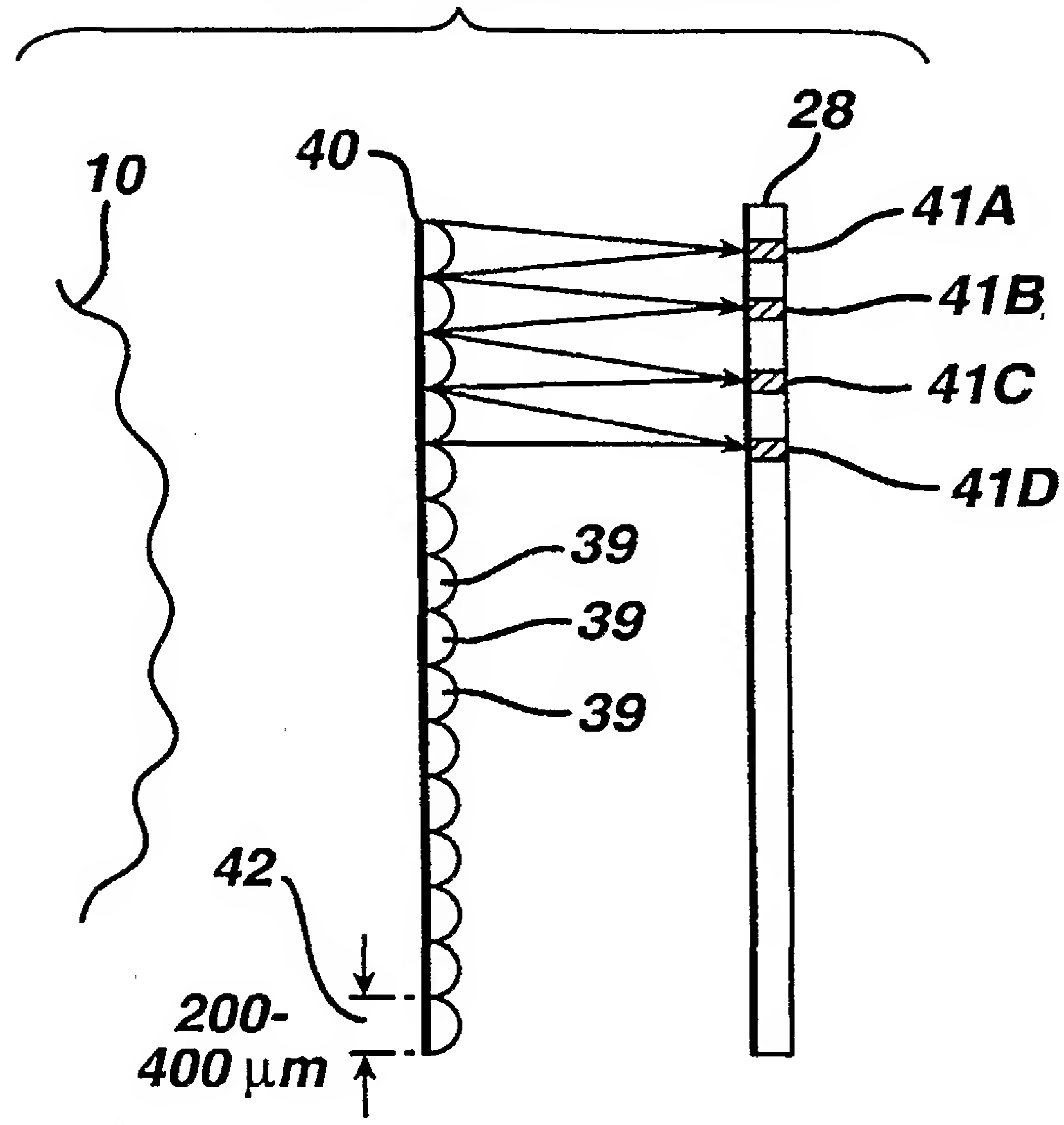

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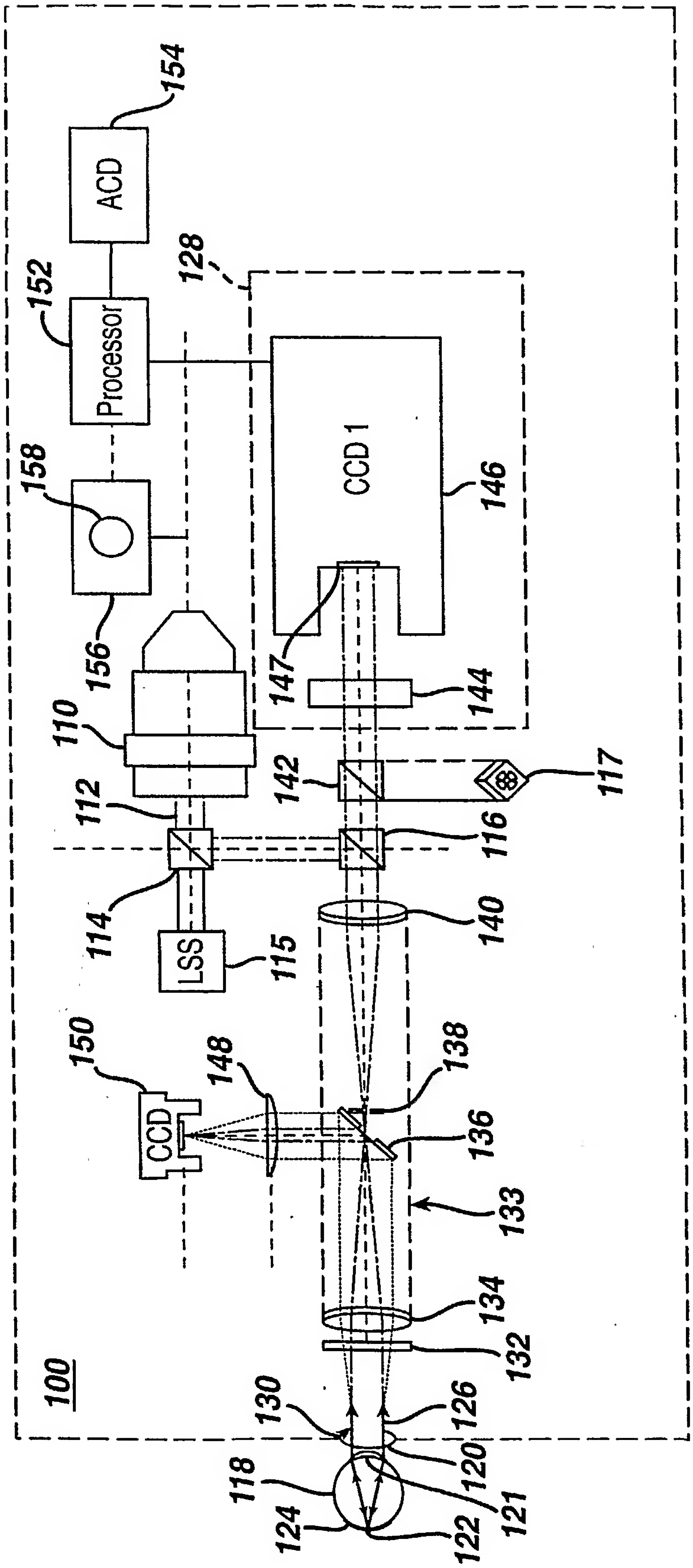
FIG. 4



100
ACD
154
Processor
152
128
158
156
CCD 1
146
147
144
110
112
142
117
114
116
LSS
115
140
150
148
CCD
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Published:
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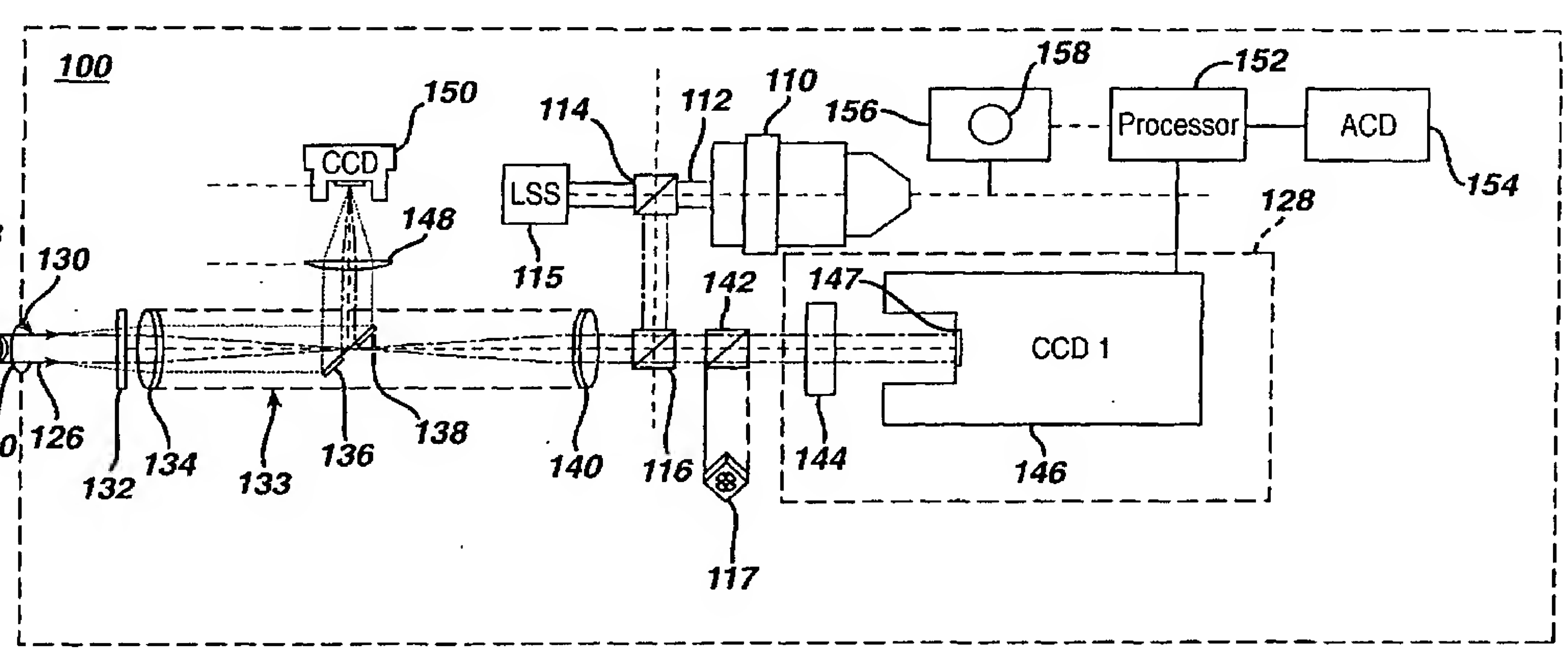
[Continued on next page]

(54) Title: WAVEFRONT MEASUREMENT



(57) Abstract: An apparatus and method for measuring wavefront aberrations. The apparatus comprises a magnification device for magnifying the wavefront, a wavefront sensor for capturing information related to the magnified wavefront, and a processor for calculating aberrations of the wavefront from the captured information. The method comprises receiving the wavefront emitted from the pupil at an adjustable lens assembly, adjusting the magnification of the adjustable lens assembly such that the magnified wavefront is optimized for use with the wavefront sensor; and passing the magnified wavefront to the wavefront sensor.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/42244

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 A61B3/103 G01J9/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 A61B G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HAMAM H: "A direct technique for calculating the profile of aberration of the eye measured by a modified Hartmann-Shack apparatus" OPTICS COMMUNICATIONS, NORTH-HOLLAND PUBLISHING CO. AMSTERDAM, NL, vol. 173, no. 1-6, January 2000 (2000-01), pages 23-36, XP004191510 ISSN: 0030-4018	1,3,4,6, 7,10,12, 14,16,17
A	page 28, left-hand column, line 19 - 25 page 28, right-hand column, line 9 - 15 page 28 - page 30, section 6.1 page 35, left-hand column, line 4 - 6 page 34, line 6 - 12 ---	5,8,9, 11,13, 15,18

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 September 2002	-4. 10. 2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Knüpling, M

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 27334 A (AUTONOMOUS TECHNOLOGIES CORP) 3 June 1999 (1999-06-03) page 13, line 26 -page 14, line 12	1,3,4,6, 7,10,12, 14,16,17
A	page 15, line 26 - line 29 page 16, line 4 - line 15 page 18, line 21 - line 26 page 31, line 8 - line 16 ---	2,5,8,9, 11,13, 15,18
X	DE 42 22 395 A (AMTECH GES FUER ANGEWANDTE MIC) 13 January 1994 (1994-01-13) column 4, line 10 - line 18	17
A	column 4, line 37 - line 43 ---	1,6,7,15
A	US 5 923 399 A (VAN DE VELDE FRANS J) 13 July 1999 (1999-07-13) column 3, line 54 - line 55 column 4, line 8 column 6, line 39 - line 63 ---	1,6, 11-13, 16-18
X	SALMON T O ET AL: "COMPARISON OF THE EYE'S WAVE-FRONT ABERRATION MEASURED PSYCHOPHYSICALLY AND WITH THE SHACK-HARTMANN WAVE-FRONT SENSOR" JOURNAL OF THE OPTICAL SOCIETY OF AMERICA - A, OPTICAL SOCIETY OF AMERICA, WASHINGTON, US, vol. 15, no. 9, September 1998 (1998-09), pages 2457-2465, XP001041250 ISSN: 1084-7529	17,18
A	page 2459, left-hand column, line 3 from bottom - right-hand column, line 15 page 2460, left-hand column, line 36 - 42 page 2461, right-hand column, line 19 - 23 -----	1,6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 01/42244

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [ ] Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. [ ] Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. [X] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[X] No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-17

   1.1. Claims: 1-16
   Wavefront sensor with control coupled to adjustable lens apparatus

   1.2. Claim : 17
   Wavefront sensor having fixation target

2. Claim : 18

   Wavefront sensor having safety circuit coupled to photodetector

Please note that all inventions mentioned under item 1, although not necessarily linked by a common inventive concept, could be searched without effort justifying an additional fee.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 01/42244

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9927334 A	03-06-1999	WO 9927334 A1	03-06-1999
		AU 740673 B2	08-11-2001
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		WO 9822016 A2	28-05-1998
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